

Beyond the Standard Model: Expectations at the LHC

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Abstract — In this talk, I review the main motivations for expecting new physics at the TeV energy scale, that will be explorable at the CERN Large Hadron Collider.

1 Introduction

The CERN Large Hadron Collider (LHC) is expected to collide the first proton beams in 2007. This machine has been designed to reach c.m. pp collision energies of 14 TeV and integrated luminosities of the order of 100 fb^{-1} per year (even higher c.m. energies will be reached in the ion-ion collision modes). Such a proton collider is the best instrument we can conceive, to our present knowledge, to explore the behavior of nature at the energy scale of order 1 TeV or, correspondingly, at length scale of order 10^{-17} cm , that is about 1/10 the ones explored so far at past and present accelerators.

The project is extremely challenging, and costly, too. It is requiring an incredible effort in different fields by a very large number of people. Then, in order to justify such an effort, one would like to have a sort of *theoretical guarantee* on its discovery potential.

The point I will try to make in my talk is about what we expect to learn from this machine from a theoretical point of view. The outcome will be that we may be approaching a *revolution* in our understanding of the physics of fundamental interactions.

2 Comparison with the CERN ppbar Collider

In order to better assess the quality of our expectations for new physics at LHC, it can be useful to recall the theoretical expectations in 1981, that is just before the starting of the CERN ppbar Collider, where proton-antiproton collisions would have been realized at the initial unprecedented c.m. energy of 540 GeV. At that time, on the basis of a huge amount of experimental data, the Standard Model (SM) of fundamental interactions had been built up. This was the end of a long and elaborated process whose final milestones were

- 1966/67 unified description of the weak and electromagnetic interactions by a gauge theory based on the group $SU(2) \times U(1)$ by Weinberg and Salam ;
- 1971 proof of the renormalizability of the theory by t'Hooft and Veltman ;
- 1973 discovery of neutral currents at CERN ;
- 1979 Nobel Prize to Weinberg, Salam and Glashow .

The outcome of the process was a very solid and predictive theory that described *observed* interactions. New particles were predicted at the starting of the ppbar Collider : the vector bosons W and Z , the Higgs boson and the top quark. At the same time, in the 70's, the Quantum Chromo-Dynamic (QCD) was developed to describe the strong interactions. One basic prediction of the theory was the asymptotic freedom, giving rise to the plethora of new phenomena connected to jet physics, also to be tested at the ppbar Collider. Altogether the physics expectations at the ppbar Collider at its starting time were solid and quite well defined.

3 Today Expectations

What are instead the present expectations, about three years before the starting of LHC ? The SM got incredibly strengthened after about 25 years of more and more accurate experimental tests, not only at the ppbar Collider, but also at LEP, TeVatron, and lower-energy experiments. We know today that the model based on the gauge group $SU(3) \times SU(2) \times U(1)$ is *the* theory that correctly describes the fundamental interactions up to energy scales $Q \sim 100$ GeV (or down to length scales $\sim 10^{-16}$ cm). There is just one missing part : the conclusive test of the mechanism of the Electro-Weak Symmetry Breaking (EWSB). The Higgs boson has not yet been observed. On the other hand, in recent years (especially at LEP), we got crucial experimental informations on the Higgs sector. First of all, we know that the SM Higgs boson must be heavier than 114.4 GeV (at 95%C.L.), as established from direct searches at LEP through the process $e^+e^- \rightarrow HZ$ [1]. A crucial, and totally independent from the latter, piece of information arises by imposing the consistency of the SM radiative-correction pattern in the precision-measurement sector. In Fig. 1, the present status of the fit of the SM radiative corrections to the electroweak

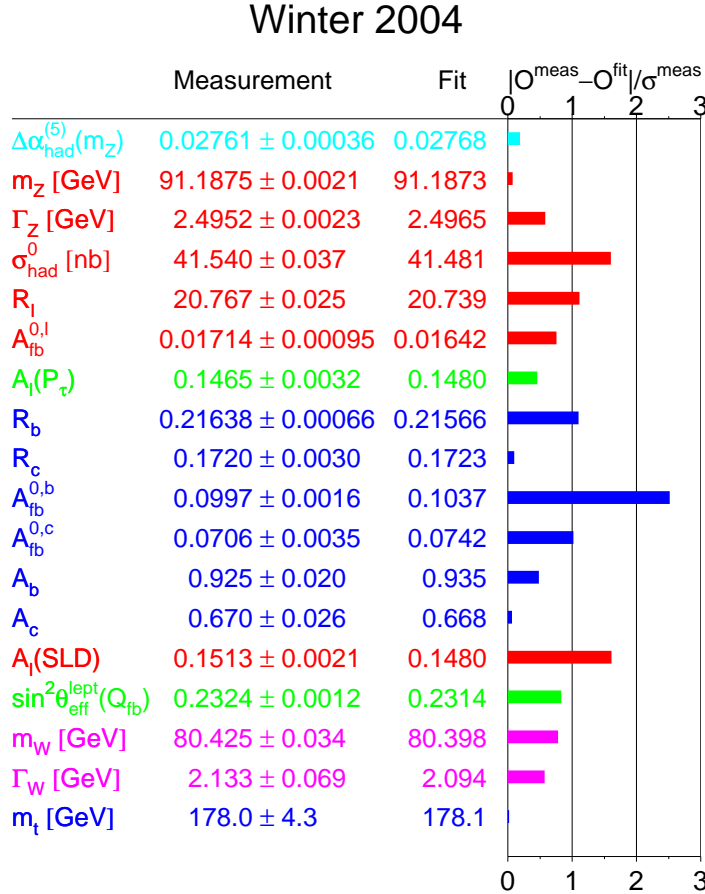


Figure 1: Summary of electroweak precision measurements [3].

precision measurements at high Q^2 is shown [2]. Apart from Z -pole data, it includes TeVatron measurements of M_W and the top mass, and the contribution to $\alpha(M_Z)$ of the hadronic vacuum polarization. The outcome of this fit is a lower limit on m_H that is milder than the direct limit, and, most importantly, a higher limit of 237 GeV (at 95%C.L.) [3], that is quite tighter than the theoretical upper limit in the minimal SM $m_H < 600 - 800$ GeV [4]. The fact that the high accuracy of the electroweak measurements (in many cases of the order of a few per mil) translates into a not-so-narrow range for m_H arises from the mild $\log m_H$ dependence of the SM radiative pattern.

A few comments on the quality of the fit are in order. Although in general one can state a good agreement with the SM predictions, there are areas that manifest some tension [5]. In Fig. 2, the m_H values obtained from the most sensitive measurements to m_H is shown. One can see that both the leptonic asymmetries and m_W tend to favorite m_H values very close to the direct experimental limit, while hadronic asymmetries prefer a larger m_H value. This effect is even enhanced when considering the two most precise m_H determinations, that come from the lepton asymmetry \mathcal{A}_ℓ , as measured by the left-right polarization asymmetry at SLD, and the forward-backward

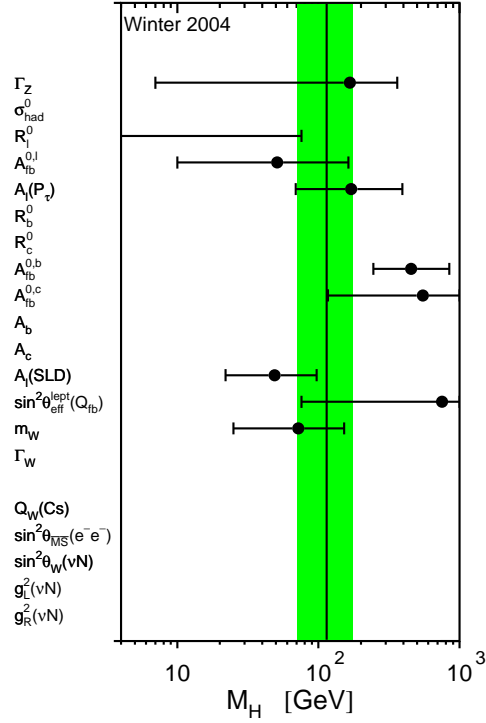


Figure 2: Higgs-boson mass determination from different observables [3].

asymmetry, $\mathcal{A}_{fb}^{0,b} = \frac{3}{4} \mathcal{A}_e \mathcal{A}_b$, measured in the $b\bar{b}$ production at LEP. Here, we define as usual $\mathcal{A}_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2}$, with g_{Lf}/g_{Rf} the left/right-handed f fermion coupling to the Z .

A similar discrepancy can be found in the two determinations of the effective electroweak mixing angle $\sin^2 \theta_{eff}^{lept}$ coming from $\mathcal{A}_\ell(SLD)$ and from $\mathcal{A}_{fb}^{0,b}$, that differ by about 3 standard deviations. In Fig. 3, the results for $\sin^2 \theta_{eff}^{lept}$ as determined starting from either all leptonic asymmetries or all hadronic asymmetries (and their combination) are compared versus m_H , placing each result at the m_H value that would correspond to the central value of the top mass, m_t [6].

There have been several discussions about the possibility of this tension to be due to some new-physics effect in \mathcal{A}_b , since, on the other hand, $\mathcal{A}_\ell(SLD)$ agrees quite well with the leptonic forward-backward asymmetries measured at LEP [6]. As seen from the fitted values of g_{Lb}/g_{Rb} in Fig. 4, such new physics would imply an excess in g_{Rb} of the order of 25% , and no relevant effect in g_{Lb} , which seems to require quite *ad hoc* models [7].

More conservatively, one can think that the $\mathcal{A}_{fb}^{0,b}$ is due either to some statistical fluctuation or to some neglected systematics. Then, the general pattern of precision measurements indicates that the SM Lagrangian describes coherently the Z and W coupling to fermions at the one-loop level, if a Higgs boson with mass not too far from the present direct lower limit will be found. Such a Higgs boson will definitely be in the realm of the LHC searches, as can be seen in Fig. 5, where the significance of the signal corresponding to the production and decay via different channels of a SM Higgs boson is shown. If the Higgs boson is there, the LHC is going to unveil it !

4 What Else ?

Is there anything else we can expect to learn at the LHC ? The answer to this question is crucially connected to another question : do we have today in high-energy physics *direct* hints of the existence of new phenomena *at the TeV energy scale* that are not predicted by the SM ?

We do not, unfortunately !

On the other hand, we are pretty sure to be at the threshold of a revolution in our knowledge of the physics of fundamental interactions. This is so for purely *conceptual* reasons, as I will try to explain in the following.

We know today that the SM is not the *final* theory. It is not, for a number of different reasons. First of all, the minimal SM does not predict the neutrino mass, that is by now a well-proved experimental fact. Second, and more

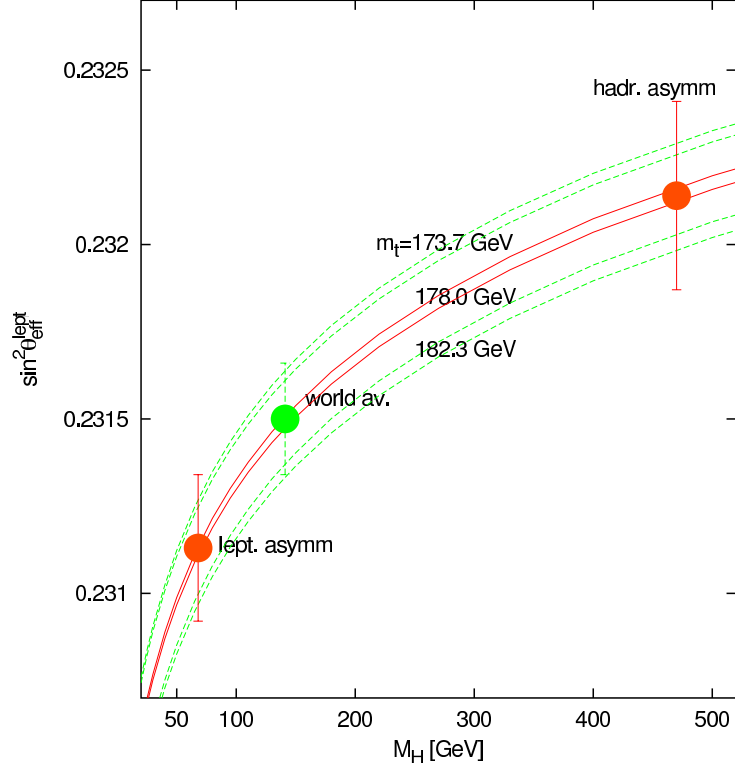


Figure 3: Determinations of $\sin^2 \theta_{eff}^{lept}$ from leptonic and hadronic asymmetries versus m_H (updated from [6]).

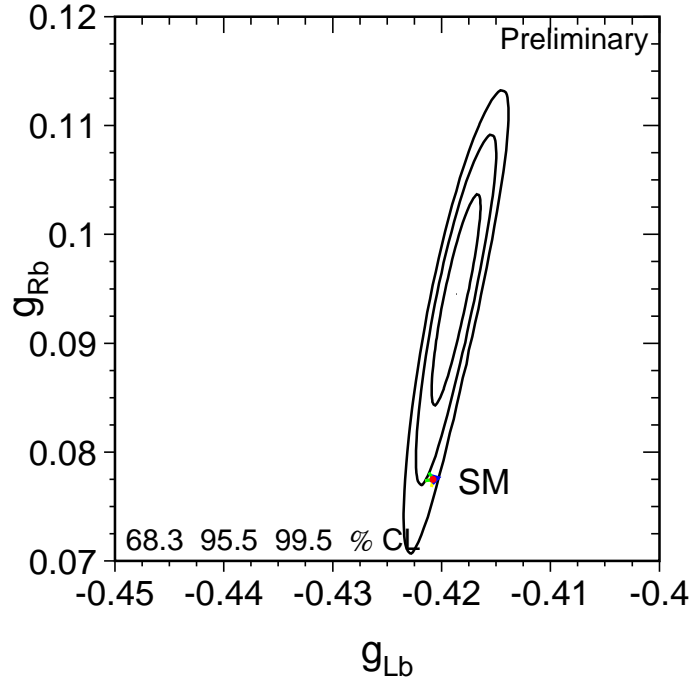


Figure 4: Determination of the left- and right-handed bottom quark coupling to the Z from precision measurements [3].

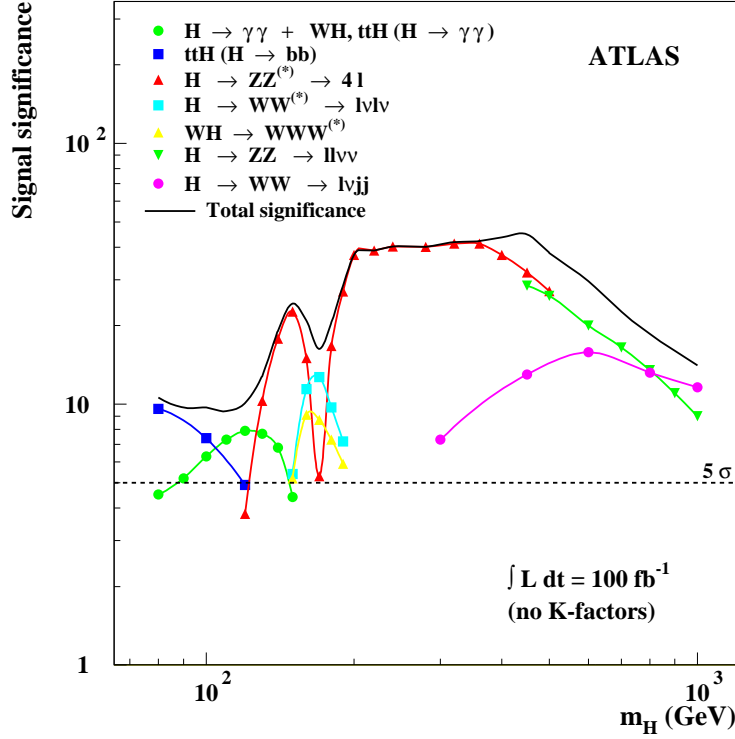


Figure 5: Significance of different SM Higgs-boson search modes in ATLAS for 100 fb^{-1} [8].

dramatically, it does not include a quantum description of the gravitational force. We know that at energy scales near the Planck mass ($M_{Pl} \sim 10^{19} \text{ GeV}$), where the gravitational force is expected to become as intense as other interactions, some radical change must enter our description of fundamental interactions.

There are then other unsolved problems in the SM, out of which I just list the best known :

- big hierarchy in energy scales ;
- missing coupling unification ;
- presence of dark matter in the universe ;
- matter-antimatter asymmetry in the universe ;
- value of the cosmological constant ;
- origin of the (many) fundamental parameters (couplings, masses, mixing angles) ;
- ...

While in general we do not know which is the energy scale relevant for the solution of most of the above issues, the *hierarchy problem* is definitely pointing us to new phenomena at the TeV scale. Most probably, also the existence of *dark matter* in the universe is implying new physics at the same scale.

Let us look into the *hierarchy problem* first. This is connected to the instability of the scalar fields under radiative corrections. The Higgs boson is the only elementary scalar field entering the SM. Contrary to other fields describing all the known particles and interactions, that benefit from the protection of symmetry principles, the radiative corrections to scalar fields behave rather wildly with respect to the theory cut-off Λ_{SM} . In particular, the corrections to the Higgs-boson mass suffer from quadratic divergences:

$$\begin{aligned}
 \delta m_H^2 &= \frac{3G_F}{4\sqrt{2}\pi^2} (2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2) \Lambda_{SM}^2 \\
 &= - \left(200 \text{ GeV} \frac{\Lambda_{SM}}{0.7 \text{ TeV}} \right)^2,
 \end{aligned} \tag{1}$$

Table 1: 90% CL limits on the scale $\Lambda_{6,i}$ (in TeV) of dimension-six operators $\mathcal{O}_{6,i}$ for constructive and destructive (\pm) interference with the SM contribution (from [9]). The limits on the operators relevant to LEP1 are derived under the assumption of a light Higgs.

	$\mathcal{O}_{6,i}$	$\Lambda_{6,i} (-)$	$\Lambda_{6,i} (+)$
LEP1	$H^\dagger \tau^a H W_{\mu\nu}^a B^{\mu\nu}$	10	9.7
	$ H^\dagger D_\mu H ^2$	5.6	4.6
	$i H^\dagger D_\mu H \bar{L} \gamma^\mu L$	9.2	7.3
LEP2	$\bar{e} \gamma_\mu e \bar{\ell} \gamma^\mu \ell$	6.1	4.5
	$\bar{e} \gamma_\mu \gamma_5 e \bar{b} \gamma^\mu \gamma_5 b$	4.3	3.2
MFV	$\frac{1}{2} (\bar{q}_L \lambda_u \lambda_u^\dagger \gamma_\mu q)^2$	6.4	5.0
	$H^\dagger \bar{d}_R \lambda_d \lambda_u \lambda_u^\dagger \sigma_{\mu\nu} q_L F^{\mu\nu}$	9.3	12.4

where the dominant contribution comes from the large top mass. If one wants to extend the validity of the SM up to very large energy scales, like M_{Pl} (where we know that the SM is going to fail), or even like a Grand-Unification-Theory (GUT) scale $M_{GUT} \sim 10^{16}$ GeV, in order to have a m_H value consistent with experiments (i.e., ~ 200 GeV), a very *unnatural* cancellation between the tree-level m_H value and the radiative correction in Eq. (1) must occur. In particular, if $\Lambda_{SM} \sim M_{Pl}$ one has to adjust the tree-level value over about 34 digits ! On the other hand, a *natural* extension of the SM should imply new phenomena at the scale $\Lambda_{SM} \sim 1$ TeV, that quite straightforwardly connects to the EWSB scale.

A pp collider of c.m. energy 14 TeV is the ideal experimental set-up where to explore the characteristics of these new phenomena.

For the last 25 years, an intense theoretical research has been trying to “parametrize” the scale $\Lambda_{SM} \sim 1$ TeV in terms of a theoretical model that should be as consistent and predictive as possible.

The main strategies adopted imply

- new symmetries ;
- new interactions ;
- new spacial dimensions ;

or a combination of them.

LEP results put strong constraints on the possible structure of the theoretical model. Precision measurements powerfully limit possible contributions to different observables coming from new physics. If one think of the SM Lagrangian as a low-energy effective theory, one expects new physics will contribute with non renormalizable higher-dimension operators. The most relevant should be the dimension-six operators $\mathcal{O}_{6,i}$, with a characteristic scale $\Lambda_{6,i}$, that enter the Lagrangian via a $\Lambda_{6,i}^{-2}$ suppressed coupling

$$\mathcal{L}_i = \pm \frac{1}{\Lambda_{6,i}^2} \mathcal{O}_{6,i}, \quad (2)$$

where the positive/negative sign refers to constructive/destructive interference with the SM model Lagrangian. In Table 1, in order to be as conservative as possible, only $\mathcal{O}_{6,i}$ operators that preserve the local and global SM symmetries, and satisfy a criterion of Minimal Flavor Violation (MFV) are considered [9]. Then, one finds that in general $\Lambda_{6,i} > 5 - 10$ TeV.

These limits seem in contradiction with the request of new physics at a scale as low as $\Lambda_{SM} \sim 1$ TeV. Actually, they can be translated into quite severe requirements on the model that wants to describe new phenomena at 1 TeV. In particular, one can see that, in order not to conflict with the bound $\Lambda_{6,i} > 5 - 10$ TeV, new physics should be *weakly* coupled, and should not contribute very much at tree level. On the other hand, *strongly* interacting models seem indeed to be excluded by the dimension-six operator analysis up to scales of the order of 5 to 10 TeV.

5 Solutions to the Hierarchy Problem

Missing any clear hint from experiments, radically different solutions have been proposed to solve the hierarchy problem connected to the naturalness of the EWSB scale.

Supersymmetry is one of the oldest [10]. It solves the problem of quadratic divergences in the Higgs sector by introducing a new symmetry that connects different-spin particle. The particle spectrum of the SM is doubled, and the properties of convergence of the corresponding field theory are drastically improved. In the limit of exact supersymmetry (i.e., degenerate particles of same quantum numbers but spin differing by $1/2$), the quadratic divergences of the scalar fields vanish. But exact supersymmetry is not realized in nature. Then, the m_H^2 one-loop corrections become proportional to the splitting in the squared masses of supersymmetric partners. Supersymmetric partner masses of the order of $(0.1-1)$ TeV would naturally solve the EWSB scale problem.

Technicolor has also been considered as a possible solution to the hierarchy problem for a long time [11]. In this case, the Higgs boson is not an elementary scalar particle, but a condensate of *technifermions* held together by a new (QCD-like) very strong interaction, with a scale $\Lambda_{TC} \sim 10^3 \Lambda_{QCD}$. Although the basic version of technicolor seems to be disfavored by LEP precision measurements, theories with a very slow running of the technicolor coupling (*walking technicolor*) can evade the LEP constraints.

Models with **large compactified extra dimensions** [12] are quite younger than the previous ones, and attack the hierarchy problem from a completely different side. The hierarchy between m_H and M_{Pl} is dissolved because the latter is not the real gravity interaction scale, that is lowered down to the TeV scale. On the other hand, there are new compactified spacial dimensions where the graviton also lives, and where most of the intensity of the “strong” gravitational interaction corresponding to a lower “ M_{Pl} ” is diluted away. In this framework, one should observe some deviation from the Newton law at small interaction distances.

In **Little Higgs models** [13], the SM symmetries are enlarged in such a way that the Higgs boson becomes a pseudo-Goldstone boson, and its mass corrections vanish at one loop. On the other hand, the two-loop m_H corrections allow to push Λ_{SM} up to about 10 TeV without giving rise to fine-tuning problems. In this case the hierarchy problem would be just postponed by an order of magnitude in the energy scale.

In **Higgsless extra-dimensional theories**, an extra dimensional component of the gauge field is interpreted as a Higgs field [14].

Although quite fascinating, many of the new models seem anyhow not to fit the electroweak precision constraints. Still further new ideas and possibilities to solve the hierarchy problem could appear before the starting of the LHC.

6 Good and Bad Points in Supersymmetry

At present, the most promising way to extend the SM and solve the hierarchy problem is to introduce supersymmetry. This statement is based on many important facts.

First, supersymmetry is potentially able to clear up all the difficulties related to the TeV-scale physics :

- it stabilizes the M_W -versus- M_{Pl} hierarchy ;
- it explains the origin of the EWSB (by the large top-quark Yukawa coupling) ;
- it makes the measured couplings at the M_W scale consistent with a GUT model;
- it predicts a light Higgs boson (the Higgs quartic coupling is fixed by gauge couplings);
- it has a delicate impact on the electroweak precision measurements (virtual supersymmetric effect are suppressed by loops, so that $\Lambda_{6,i} \sim 4\pi\Lambda_{SM}$) ;
- it can have a delicate impact on FCNC processes ;
- it can naturally explain the origin of the dark matter .

Second, supersymmetry is a weakly-coupled theory. It dramatically improves the convergence of the radiative-correction pattern, and is reliably computable. It allows accurate and consistent theoretical predictions even at energy scales much higher than 1 TeV. It could be extended up to scales not too far from M_{Pl} , or even support the

desert hypothesis, that very ambitiously implies that, after including supersymmetric partners at the TeV scale, no new phenomenon appears when increasing the energy up to the GUT scale.

The fact that supersymmetry is able to reconcile the SM with a GUT model is considered today the most direct phenomenological evidence for supersymmetry. The value of the electroweak coupling constants $\sin^2 \theta_W$ and $\alpha(M_Z)$ measured at LEP evolve up to the GUT mass scale M_{GUT} into a unified constant α_{GUT} that, when evolved back to the M_Z scale in the SU(3) coupling, gives by far a too low value for the strong coupling constant $\alpha_s(M_Z)$. Also, the unification scale M_{GUT} would induce a too fast proton decay. All this can be cured quite naturally by the introduction of supersymmetry with partner masses at the TeV scale [15]. The coupling evolution slows down, and $\alpha_s(M_Z)$ can match its experimental value, while M_{GUT} is increased up to a value consistent with the limits on the proton decay rate.

So far, everything looks perfect with supersymmetry. But there are two bad points, one on the experimental side and one on the theoretical side, that have weakened up to now the cause for supersymmetry ! After more than 20 years of experimental searches for supersymmetric partners, no positive signal has been detected. We just got limits on the allowed parameter space.

The implications of this fact are somehow made less dramatic by the second bad point: there is a remarkable arbitrariness in the construction of theoretical models for the supersymmetry breaking on which the spectrum of the supersymmetric partners is crucially based. The only solid constraint comes from the fact that, in order to stabilize the hierarchy M_W -versus- M_{Pl} , the partner masses should be in the range $\sim (0.1 \div 1)$ TeV.

Anyway, since we do not want the breaking to spoil the good convergence properties of the theory, the spontaneous breaking of supersymmetry should be susceptible to be parametrized by *soft* operators, of dimension ≤ 3 [16]

$$\begin{aligned} -\mathcal{L}_f &= Y_{\alpha\beta\gamma} \Phi^\alpha \tilde{\Phi}^\beta \tilde{\Phi}^\gamma + \mu \tilde{H}_u \tilde{H}_d + h.c. \\ -\mathcal{L}_{soft} &= m_\alpha^2 \Phi^{*\tilde{\alpha}} \Phi^\alpha + M_a \lambda^a \lambda^a + A_{\alpha\beta\gamma} \Phi^\alpha \Phi^\beta \Phi^\gamma + B\mu H_u H_d + h.c. \\ \text{with} \quad \Phi^\alpha &= Q_L, u_L^c, d_L^c, L_L, e_L^c, H_u, H_d. \end{aligned}$$

This implies introducing 108 new parameters !

In general, in any realistic supersymmetry breaking model, there are two energy scales involved : the supersymmetry breaking scale \sqrt{F} that is the VEV of the relevant auxiliary fields in the supersymmetry breaking sector, and the messenger scale \mathcal{M} that is associated to the interactions that transmit the breaking to the observable sector ($\mathcal{M} \sim 30 \text{ TeV} \div M_{Pl}$). The latter give rise to soft terms for the scalar and gaugino masses :

$$m_f^2 \sim c_f \frac{F^2}{\mathcal{M}^2}, \quad M_a \sim d_a \frac{F}{\mathcal{M}}. \quad (3)$$

These mass parameters have then to be evolved through the renormalization group equations (RGEs) from the \mathcal{M} scale down to the TeV scale, the one relevant to experiments. Experiment task, after the supersymmetry discovery, will be to determine \mathcal{M} and the structure of the coefficients c_f, d_a .

FCNC constraints imply that squark and slepton with equal quantum numbers are either almost degenerate in mass, or almost diagonal in the Yukawa matrices. Different breaking schemes that verify these conditions quite naturally have been proposed : gauge mediation (GMSB) (with quite a low \mathcal{M}) [17], anomaly mediation (AMSB) [18], gaugino mediation [19].

7 Tensions in the cMSSM

In order to maximize the predictive power by using as few basic parameters as possible, most of the phenomenological studies today have been done in the constrained minimal supersymmetric standard model (cMSSM), even known as minimal supergravity (mSUGRA) [20]. In this framework, a quite large supersymmetry breaking scale ($\sqrt{F} \sim 10^{11}$ GeV), is transmitted via gravitational interactions ($\mathcal{M} \sim M_{Pl}$) down to a mass splitting in the observable sector of the needed amount (~ 1 TeV). The coefficient c_f, d_a are assumed to be universal, and are parametrized by a common scalar mass m_0 and a common gaugino mass $M_{1/2}$ at the scale M_{GUT} . Furthermore, radiative EWSB is imposed. Indeed, in this model there are two Higgs doublets, and one of the Higgs scalar mass parameter, $m_{H_u}^2$, can develop a negative value (that breaks the electroweak group $SU(2) \times U(1)$) just as an effect of the RGEs evolution from the high scale down to M_W . From the minimization of the Higgs effective potential one gets then the condition

$$\mu^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} - \frac{1}{2} M_Z^2. \quad (4)$$

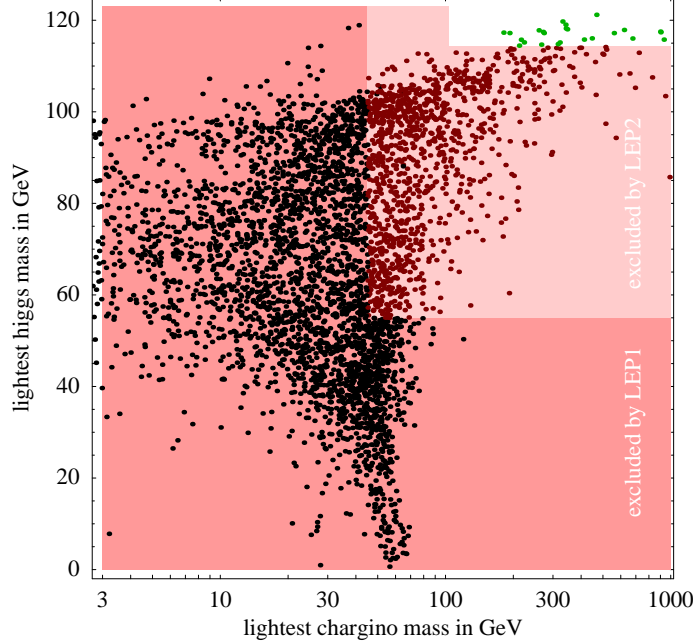


Figure 6: Scatter plot of the chargino and Higgs mass obtained by sampling the parameter space in mSUGRA. The regions excluded by LEP1 and LEP2 searches are shown [9, 22].

where $\tan \beta = \langle H_u^0 \rangle / \langle H_d^0 \rangle$ is the ratio of the two Higgs vacuum expectation values (the sign of μ remains undetermined). For not too small $\tan \beta$ values, one has :

$$M_Z^2 \sim -2\mu^2 - 2m_{H_u}^2, \quad (5)$$

with all the parameter meant at low energy. As the result of RGEs evolution, one can express the right-hand side of Eq. (5) as a linear combination of initial (high-scale) squared mass parameters, m_0 and $M_{1/2}$, a common trilinear coupling A_0 , and μ . Then, taking into account LEP limits on the charginos ($m_{\chi_1^\pm} > 103.5$ GeV [21]) and the light Higgs boson h , the above equation implies a non-trivial cancellation between terms that are individually quite larger than M_Z^2 . A fine-tuning of the order of per cent is already implied by the present experimental limits for the cMSSM, as Fig. 6 shows [9, 22]. One can easily check that the present light Higgs-mass limit pushes the squark masses up to quite high values. The lightest Higgs boson in the cMSSM has a tree-level mass lower than M_Z that would strongly conflict with the limit $m_h^{exp} > 114$ GeV (for a quite heavy pseudoscalar) [23]. On the other hand, large radiative corrections are predicted at one loop

$$m_h^2 \simeq M_Z^2 \cos^2 \beta + \frac{2\alpha_w m_t^4}{2\pi M_W^2 \sin^2 \beta} \log \frac{\tilde{m}_t^2}{m_t^2}. \quad (6)$$

In order, to be compatible with the limit $m_h^{exp} > 114$ GeV, the one-loop correction implies both a large mixing in the stop sector and a heavy stop mass, $\tilde{m}_t > 3.8m_t \sim 700$ GeV.

These tensions with experimental data in the cMSSM have motivated theorists to consider alternative (less constrained) models, where the tree-level Higgs mass is naturally larger than M_Z [24, 25, 26].

8 Supersymmetry Signatures at the LHC

If supersymmetry is there, it will be hard for the LHC to miss it ! Typical experimental signatures corresponding to the production of supersymmetric partners are in general quite striking. The production and decay of very massive new particles (most of the times the strongly-coupled squarks and gluinos) give rise to large effective mass (M_{eff}) events with high jet multiplicity and high missing p_T , arising from the presence of the undetected stable lightest neutralino in the particle decay chains. Fig. 7 shows how the corresponding $M_{eff}(= E_T^{miss} + \sum_{jet} E_T^{jet})$

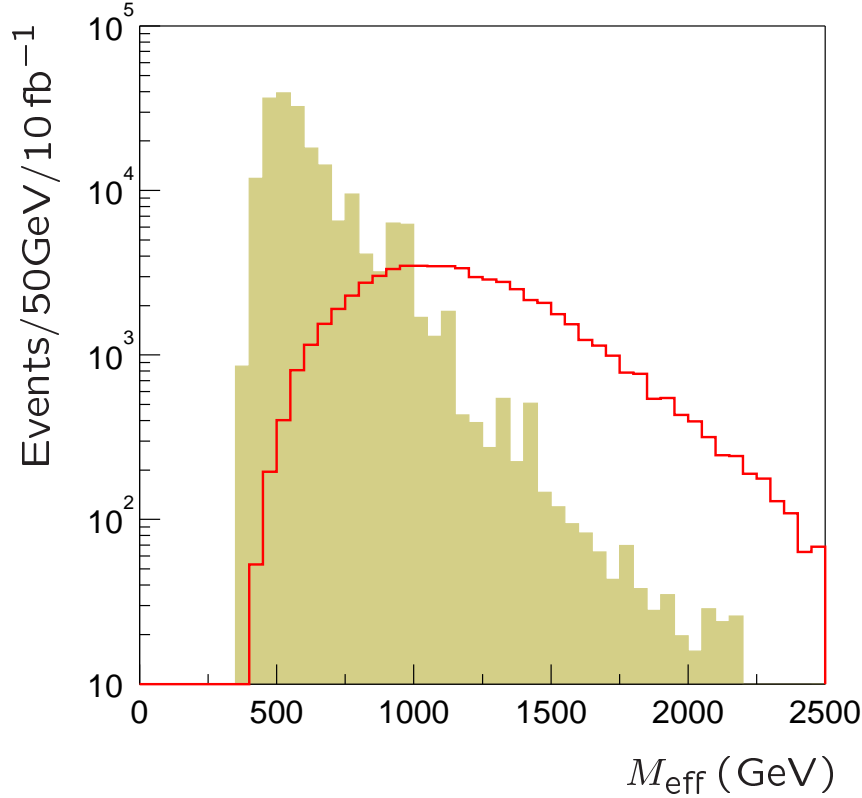


Figure 7: M_{eff} distribution for a typical mSUGRA point and SM backgrounds after cuts [27].

distribution in mSUGRA compares with the SM background, for $M_{1/2} = 300$ GeV, $m_0 = 100$ GeV, the trilinear scalar coupling $A_0 = 0$, $\tan \beta = 10$ and $\text{sgn } \mu = +$. This is in general a very robust signature, and will be hard to miss it !

In Fig. 8, the $(m_0, M_{1/2})$ parameter space covered by the E_T^{miss} signature for $\tan \beta = 10$, and integrated luminosities of 0.1, 1 and 10 fb^{-1} is shown. One month of running at “low” luminosity ($\sim 10^{33} \text{ cm}^{-2}\text{s}^{-1}$), that roughly corresponds to the 1 fb^{-1} curve, will be sufficient for the discovery of squark and gluinos as massive as 1.5 TeV !

Additional signatures have also been considered. In Fig. 9, the LHC search limits based on the presence of a number of isolated leptons in the final state are considered. In other supersymmetric models, like in the GMSB model, isolated photons can be present in the final state, or even charged heavy semi-stable particles, behaving like heavy muons in the detectors [29].

In Fig. 10, the expected reach in the GMSB model parameter Λ for different integrated luminosities is shown [30]. In Fig. 11, the expected reach for integrated luminosities of 1, 10 and 100 fb^{-1} is presented versus the AMSB model parameters [30].

The coverage of the parameter space that is relevant to the solution of the hierarchy problem is in general guaranteed at the LHC for any supersymmetry-breaking model considered !

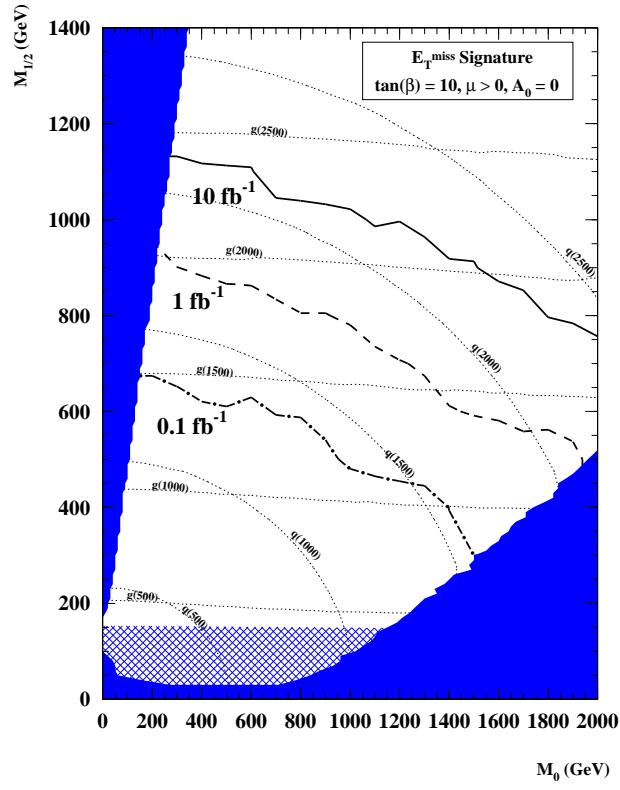


Figure 8: LHC search limits for the E_T^{miss} signal in cMSSM, with integrated luminosities of 0.1, 1 and 10 fb^{-1} [28].

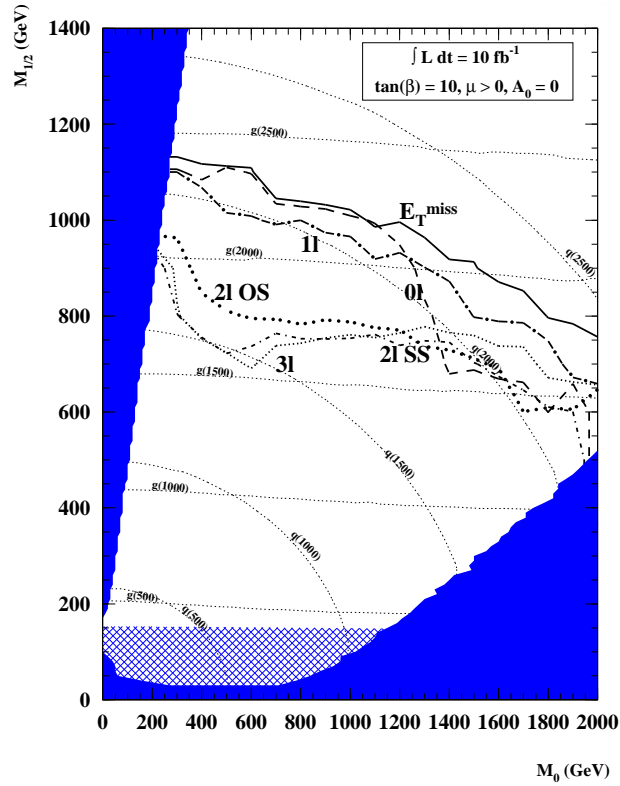


Figure 9: LHC search limits for the cMSSM model in various leptonic channels for 10 fb^{-1} [28].

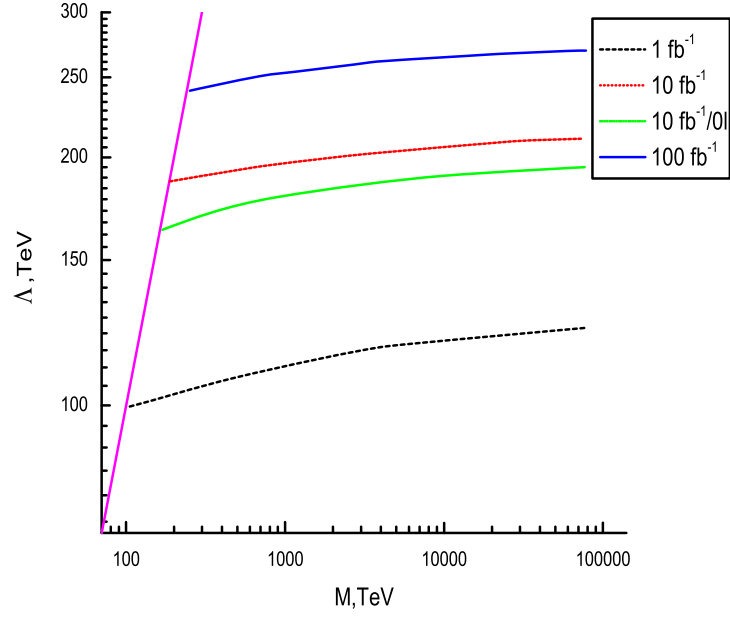


Figure 10: The sensitivity reach of ATLAS to a GMSB signal [30].

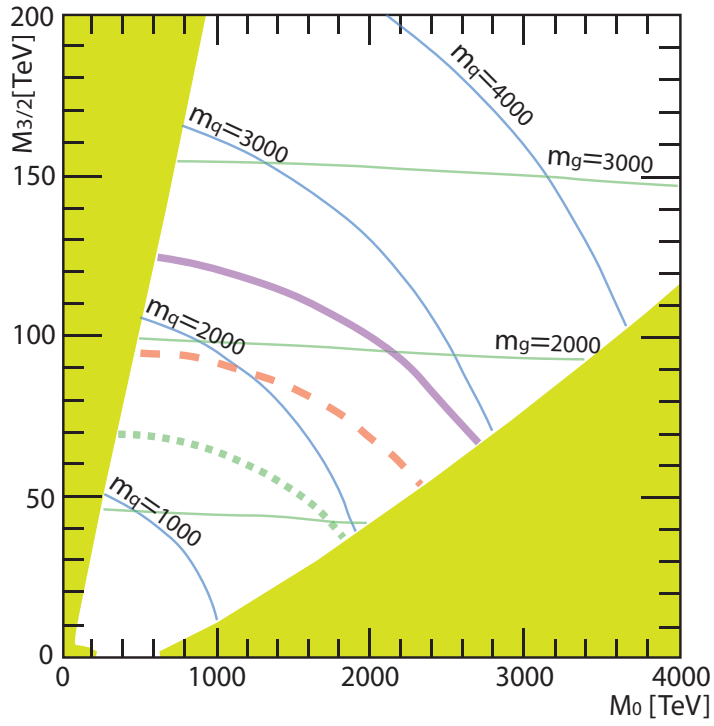


Figure 11: The sensitivity reach of ATLAS in the AMSB parameter space for luminosities of 1 (short-dashed), 10 (long-dashed) and 100 (solid) fb^{-1} [30].

9 Dark Matter and LHC Searches

The need for *dark matter* is a long-standing issue in modern cosmology [31]. A number of astrophysical and cosmological observations indicate that a substantial fraction (perhaps as much as 30%) of the energy density in the Universe is due to non relativistic, non baryonic, non luminous matter. The presence of an “unseen” component of matter in individual galaxies has been well established by looking at the rotation curve $v(r)$ of galaxies (on a sample of over one thousand spiral galaxies). The Kepler’s third law predicts

$$v(r) = \sqrt{\frac{GM(r)}{r}}, \quad (7)$$

where r is the radial distance from the galactic center. As can be seen in Fig. 12, the observed curve, instead of behaving as $1/r^{1/2}$, flattens out at large distances from the luminous disk. This implies a mass increasing like

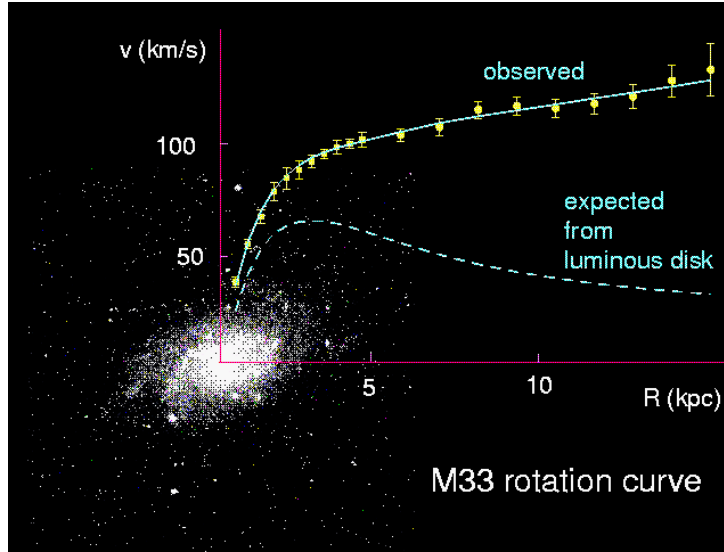


Figure 12: The observed rotation curve of the dwarf spiral galaxy M33 extends considerably beyond its optical image (shown superimposed), from [33].

$M(r) \propto r$ in the region where no luminous mass can account for such an increase. In particular, in order to explain the galactic rotation curves, one needs about one order of magnitude more matter in the galaxies than the one corresponding to the “seen” component. It is not easy to explain rotation curves via possible modifications of the Newton law. Altogether, this evidence is quite tight and solid, not depending on particular cosmological assumptions.

The microscopic nature of dark matter is presently not known. In particle physics, one can quite naturally imagine that it is made of *thermal relics*. A thermal relic is a stable neutral particle that was in thermal equilibrium at the starting universe, and, due to the universe expansion, at a certain time (*freeze-out* time) decouples. The present *relic density* of these particles, Ω_{DM} , depends on the moment they decouple, that, in turn, depends on the time when the particle annihilation rate equals the expansion rate of the universe. Then, one has

$$\Omega_{DM} \propto \frac{1}{\langle v_a \sigma_{ann} \rangle}, \quad (8)$$

where v_a is the relative velocity of two annihilating particles and the constant of proportionality is computable. By using the recent accurate WMAP measurement $\Omega_{DM} h^2 = 0.113 \pm 0.009$ (where $h = H_0/100 \text{ km/s/Mpc} = 0.7$ is the current Hubble expansion rate) [32], one finds

$$\langle v_a \sigma_{ann} \rangle \sim 1 \text{ pb} . \quad (9)$$

This rate is the one characteristic of electroweakly interacting particles with mass m of the order of 100 GeV, that is $\sigma_{ann} \sim \alpha^2/m^2$! As far as we know today, it could have been different from this value by orders of magnitude.

All this leads quite naturally to the *weakly interacting massive particle* (WIMP) hypothesis : dark matter is made of stable neutral particles as heavy as (100 – 1000) GeV, weakly coupled to ordinary matter. This implies that both production cross sections and signatures of this new kind of matter are of interest for the LHC ! High p_T jets with large missing transverse energy corresponding to WIMP's production would naturally emerge on the SM background !

There is a number of different theoretical models for the EWSB that can predict WIMP's. The oldest is supersymmetry, that, for conserved R parity, predicts a stable lightest neutralino very well compatible with a WIMP interpretation. Fig. 13, from [34], compares the reach of LHC and future e^+e^- linear colliders in the cMSSM parameter space with the region that is compatible with the WMAP relic-density determination.

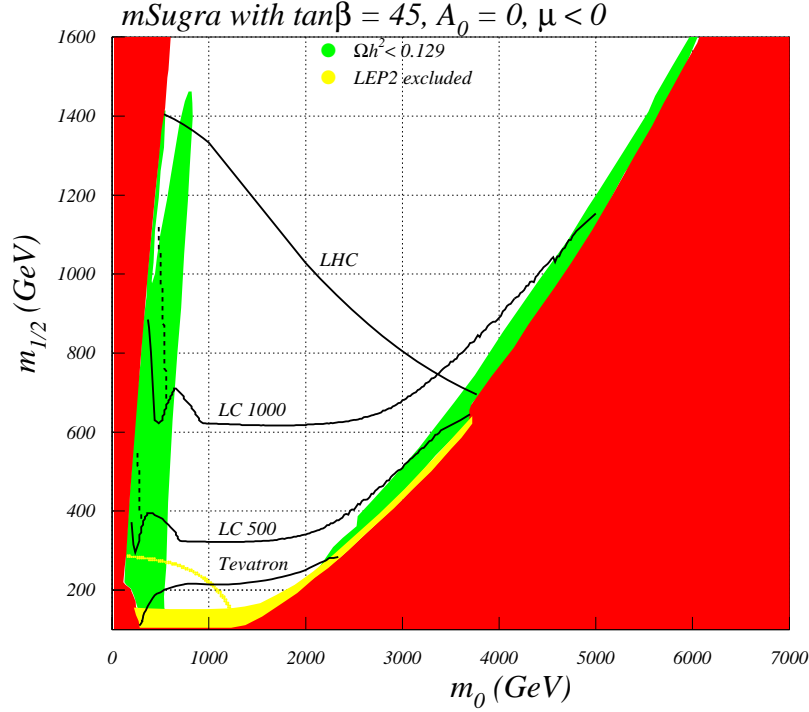


Figure 13: Reach of the LHC and a linear collider (LC) with $\sqrt{s} = 0.5$ and 1 TeV, compared with the (green) region compatible with a neutralino hypothesis for the WIMP's in the cMSSM, from [34].

More recently, different theoretical frameworks giving rise to WIMP-like particles, like Universal-Extra-Dimension and Little-Higgs models, have been considered [35]. In general, the requirements to be fulfilled by the new model are: existence of new particles; new symmetry that makes one of the new particles stable; possibility to adjust the model parameters to make the lightest new stable particle neutral, and with the proper thermal relic density.

Many possibilities can be considered, and the LHC will be extremely helpful in discriminating among them !

10 Conclusions

The EWSB sector of the SM is not yet completely tested. The Higgs boson is still to be found, and, eventually, its properties are to be tested. In order to stabilize the EWSB scale, new physics at the TeV scale is required. This holds in any of the following cases ;

- the Higgs boson is light (< 200 GeV)
- the Higgs boson is heavy (> 200 GeV)
- the Higgs boson will not be found.

There are presently quite a few theoretical models that try to solve (or at least to postpone) the M_W -versus- M_{Pl} hierarchy problem. Unfortunately, for no one of them there is today any direct experimental evidence. The LHC will be able to discriminate among them.

Given our confidence in the need for new physics at the TeV scale on the one hand, and, on the other hand, the fact that up to now no model is supported experimentally, the *discovery* potential of the LHC is enormous, if *discovery* stands for finding *unforeseen* phenomena. We are likely to be at the edge of a revolutionary time for the physics of fundamental interactions !

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